

Giant Linear Magneto-resistance in Nonmagnetic PtBi₂

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We synthesized nonmagnetic PtBi₂ single crystals and observed a giant linear magneto-resistance (MR) up to 684% under a magnetic field $\mu_0 H = 15$ T at $T = 2$ K. The linear MR decreases with increasing temperature, but it is still as large as 61% under $\mu_0 H$ of 15 T at room temperature. Such a giant linear MR is unlikely to be described by the quantum model as the quantum condition is not satisfied. Instead, we found that the slope of MR scales with the Hall mobility, and it can be well explained by a classical disorder model.

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Materials exhibiting large magneto-resistance (MR) can not only be utilized to enlarge the sensitivity of read/write heads of magnetic storage devices, e.g., magnetic memory¹ and hard drives², but also stimulate many fundamental studies in material physics at low temperatures^{3,4}. Generally speaking, the ordinary MR in non-magnetic compounds and elements⁵ is a relatively weak effect and usually at the level of a few percent for metals⁴. Moreover, a conventional conductor under an applied magnetic field exhibits a quadratic field dependence of MR which saturates at medium fields and shows a relatively small magnitude. Owing to the rich physics and potential applications, the large linear MR effect has drawn renewed interest recently.⁶⁻⁸ There are two predominant models used to explain the origin of such large linear MR effect, namely, the quantum model⁹ and the classical model¹⁰. The quantum model is proposed for materials with zero band gap and linear energy dispersion, such as topological insulators¹¹, graphene¹², Dirac semimetals like SrMnBi₂¹³, and the parent compounds of iron based superconductors¹⁴. Quantum linear MR occurs in the quantum limit when all of the electrons fill the lowest Landau level (LL)⁹. In contrast, the classical linear MR is dominated by disorder. Materials showing the classical linear MR include highly disordered systems¹⁵, and weakly disordered samples with high mobility^{7,16-18}, thin films, and quantum Hall systems¹⁹. However, it is interesting that the classical linear MR has also frequently been reported in materials with linear dispersions, such as the topological insulator Bi₂Se₃²⁰, graphene⁷, and the Dirac semimetal Cd₃As₂¹⁷, which may be due to their large mobility. Even weak disorder could induce linear MR in high-mobility samples^{16,17}. When the carrier concentration

is too high for the quantum limit, the linear MR may be described by classical model for disordered systems^{7,18}.

In this Letter, we synthesized high quality single crystals of nonmagnetic PtBi₂ and investigated the magneto-transport properties. We observed a giant positive linear MR up to 684% under $\mu_0 H = 15$ T at $T = 2$ K. MR decreases with increasing temperature, but MR of 61% is still achieved under a magnetic field of 15 T even at room temperature. Regarding the origin of the linear MR, the close relationship between the MR and the Hall mobility implies that the observed linear MR should not be attributed to the quantum origin, but may be explained by the classical model.

The PtBi₂ single crystals were synthesized using a self-flux method. Powders of the elements Pt (99.97%) and Bi (99.99%), both from Alfa Aesar, were thoroughly mixed together in an atomic ratio of Pt:Bi = 1:8, before being loaded into a small alumina crucible. The crucible was then sealed in a quartz tube in Argon gas atmosphere. During the growth, the quartz tube was slowly heated up to 1273 K and kept at the temperature for 10 h. Finally it was slowly cooled to 873 K at a rate of -3 K/h, followed by centrifugation to remove the excessive Bi. The resulting single crystals are large plates with a typical dimension of $3 \times 3 \times 0.05$ mm³. We cut the single crystal into a rectangle of about $1 \times 0.4 \times 0.05$ mm³ for transport measurements. The stoichiometry and structure of these single crystals were checked using Energy-dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) measurements. All transport measurements were carried out in an Oxford-15 T cryostat with a He4 probe in a Hall-bar geometry, using Keithley 2400 sourcemeters and 2182A nanovoltmeters.

As illustrated in Fig. 1(a), PtBi₂ has a layered pyrite crystal structure with the space group of P-3 (No. 147)²¹. Fig. 1(b) shows the X-ray diffraction pattern of the PtBi₂ single crystals. Only multiple reflections of (0 0 *l*) planes can be detected, consistent with the layered crystal struc-

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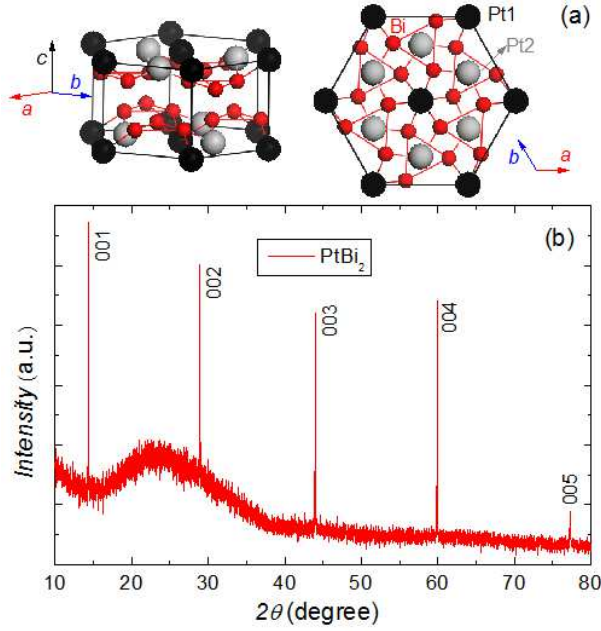


FIG. 1. (color online) (a), The crystal structure of PtBi_2 . (b), X-ray diffraction patterns of PtBi_2 single-crystal sample.

ture depicted in Fig. 1(a). The interplane spacing is determined to be 6.16 Å, agreeing well with the previous reported value²¹.

The temperature dependence of in-plane resistivity curves under magnetic fields ($\parallel c$) of $\mu_0 H = 0, 5, 10$ and 15 T are displayed in Fig. 2(a). In zero field, the room temperature resistivity is $1.1 \mu\Omega \text{ m}$ and decreases to $0.13 \mu\Omega \text{ m}$ at 2 K, yielding a residual resistivity ratio (RRR) of 8.5. When a field is applied, the resistivity increases rapidly, corresponding to a large positive magnetoresistance ($\text{MR} = \Delta\rho(H)/\rho(0) = \rho(H)/\rho(0) - 1$). By measuring the magnetic field dependence of resistivity at fixed temperatures, we have observed giant, non-saturating linear MR, which can reach 684% under $\mu_0 H = 15 \text{ T}$ at $T = 2 \text{ K}$ [Fig. 2(b)]. To our surprise, the room temperature magnetoresistance is still as large as 61% in a field of 15 T.

The non-saturating, large linear magnetoresistance in PtBi_2 is quite unusual and contradicts with the semiclassical transport theory. For conventional metals, the MR exhibits quadratic field-dependence in the low field range and saturates under high field, and the MR is usually of a small value. For a system with open orbits or Fermi surfaces, unsaturated MR with quadratic field dependence (or linear field dependence, which critically depends on the Fermi surface and the relative orientation of magnetic field) could appear even under high field along the open orbits while in other directions MR would still show saturated behavior. As a result, linear field dependence of MR could be observed in polycrystal sample owing to averaging effect^{22–24}. Such a giant, non-saturating linear MR in the PtBi_2 single crystal certainly does not fit into

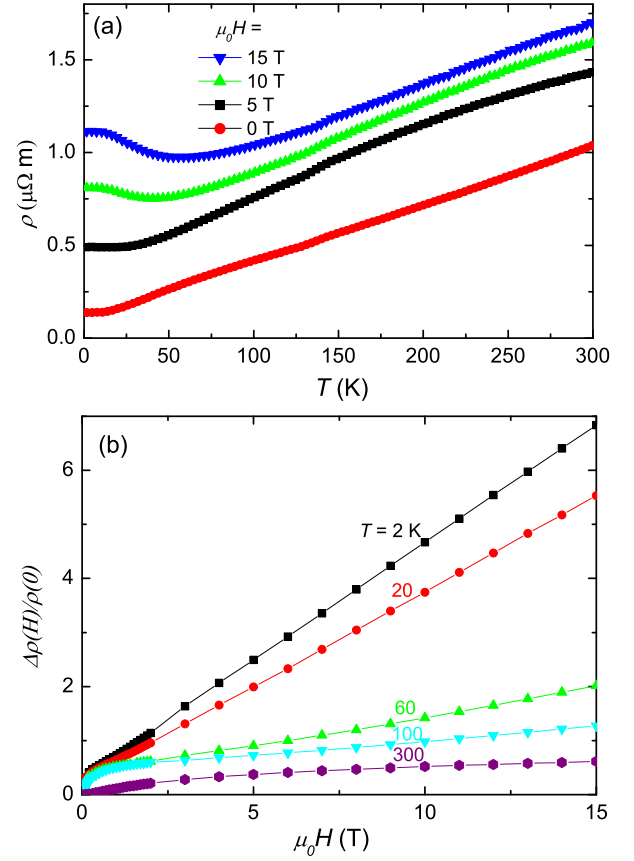


FIG. 2. (color online) (a), In-plane resistivity ρ as a function of temperature T at a series of out-of-plane magnetic fields $\mu_0 H = 0, 5, 10$ and 15 T. (b), The magnetoresistance ($\text{MR} = \Delta\rho(H)/\rho(0) = \rho(H)/\rho(0) - 1$) as a function of magnetic field $\mu_0 H$ at a series of temperatures $T = 2, 20, 60, 100$ and 300 K.

these two categories.

We first consider a quantum explanation for the observed linear MR phenomenon in the framework developed by Abrikosov⁹. Following this theory, linear MR will appear in the quantum limit, when $\hbar\omega_c$ exceeds the Fermi energy E_F and all the electrons occupy the lowest LL. In such a limit, the quantum magnetoresistivity is calculated as $\rho_{xx} = N_i B / \pi n^2 e$, where n and N_i are the electron density and the concentration of scattering centers, respectively. The equation is valid under the condition, $n \ll (eB/\hbar)^{3/2}$. That is, the quantum linear MR would appear when $B \gg (\hbar/e)n^{3/2}$. In Fig. 3(a), we have plotted the temperature dependence of Hall coefficient (R_H). The Hall resistivity (ρ_{yx}) is linearly dependent on the magnetic field (not showing here) and thus we use a single-band model to estimate the charge carrier density, i.e., $n = 1/eR_H$ and to calculate the critical magnetic field of $(\hbar/e)n^{3/2}$. We find that, even at 2 K, it needs $\sim 271 \text{ T}$ to satisfy the quantum condition, which is far higher than the maximum field of 15 T in our experiments. Therefore, the observed linear MR in PtBi_2

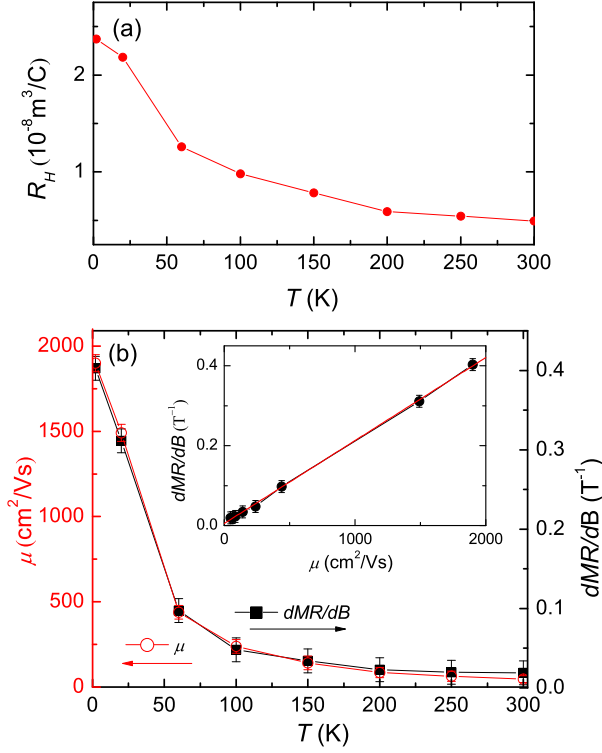


FIG. 3. (color online) (a), Hall coefficient versus temperature for PtBi₂. (b), Hall mobility (red hollow circles) and dMR/dB (black solid squares) versus temperature. The inset displays the dMR/dB versus Hall mobility.

is unlikely to be explained by the quantum model.

Instead, the classical disorder models¹⁰ may provide a reasonable explanation for the presence of linear MR in PtBi₂. In the disorder network model, the linear MR appears when the local current density gains spatial fluctuations in both magnitude and direction, as a result of inhomogeneous carrier or mobility distribution^{10,17}. Such classical linear MR phenomena have been observed in various disordered systems, such as Bi₂Se₃²⁰, n-doped Cd₃As₂¹⁷, and epitaxial graphene on SiC⁷. In the classical model, the slope dMR/dB is predicted to be proportional to the Hall mobility: $dMR/dB \propto \mu$. Indeed, the dMR/dB, which is defined as the slope of the linearly fitting line of the linear region of MR at higher fields, exhibits the same temperature dependence (see the black solid squares in Fig. 3(b)) as the Hall mobility (red hollow circles). The curve of dMR/dB versus μ can be fitted linearly very well, as shown in the inset of Fig. 3(b). This strongly suggests that the origin of the observed linear MR in our sample could be classical.

This classical origin can be further verified by scaling the inverse Hall mobility with the crossover magnetic field (B^*)⁷. We define the B^* , marked by the arrow, as the crossing point of linear fits at the low and high field regimes, which are shown as blue dashed lines in the in-

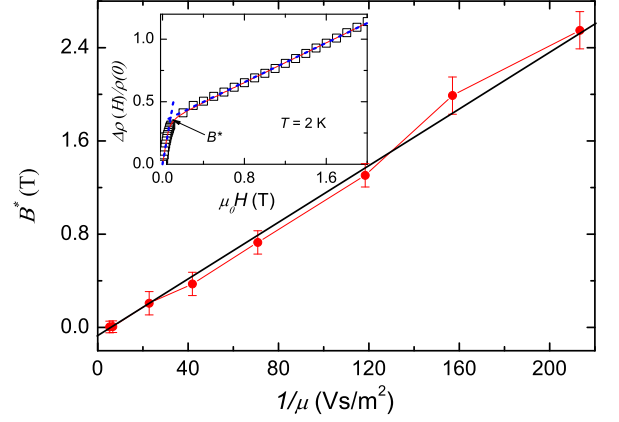


FIG. 4. (color online) B^* versus inverse Hall mobility. Inset: Field dependence of MR (black hollow squares) at $T = 2$ K. The two dashed blue lines are the linear fits at the low and high field regimes. The point B^* , marked by the arrow, is defined as the crossing point of these two lines.

set of Fig. 4. In the classical model, the crossover field is predicted to be linearly proportional to the inverse Hall mobility: $B^* \propto 1/\mu$. Fig. 4 shows B^* versus inverse Hall mobility, which displays good linear dependence, consistent with the classical model well. This further confirms that the origin of the observed linear MR could be classical. The disorder in the single-crystalline samples could come from the Bi-site vacancies. The occupation of Bi sites obtained by EDX is around 94%, which confirms the existence of Bi-site vacancies.

In summary, we performed detailed magnetotransport property measurements in the PtBi₂ single crystals. PtBi₂ exhibits very large linear magnetoresistance (684% in 15 T field at 2 K). The giant linear MR can scale well with the mobility. Our work indicates that the giant linear MR could arise from the classical origin, which makes PtBi₂ an appealing system for both practical use and further investigation on its physic properties.

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